Chapter 2
Human Hand Motor Control Studies

Abstract This chapter aims to give a brief overview on the complexity that is typical of hand motor control studies. Starting from biomechanical hand models to recent theories on motor control in grasping tasks, in this dissertation the important factors which affect grasp proprieties are dealt. The mechanical structure of human hand is extremely complex and difficult to model; its rigid internal framework is made by 27 bones that are moved by 18 intrinsic muscles and 18 extrinsic muscles coupled by a network of tendons. To have a simple hand model, at least 23–24 DoFs are needed: 4 DoFs for each finger, 5 for the thumb, 1 for the radioulnar joint, and 2 at the wrist. In a more detailed model, the number of DoFs increases just taking into account the hand's capability to create a palmar arch when it closes. A complete biomechanical model includes 36 muscles coupled to the bones by a complex tendons network; moreover, several biomechanical constraints have to be included in the model. Joint limits or finger dimensions are clear examples of constraints which can affect the interaction of the hand with the world, and additional constraints arise from the coupling of tendons and muscles. Some muscles span several phalanges, making it difficult to move only one joint independently; for example, the flexor digitorum superficialis (FDS) and extensor digitorum communis (EDC) muscles are divided on each finger; therefore, a contraction of these muscles engages several hand joints. Understanding how humans exploit biomechanics and sensory feedback of hand in everyday tasks is a challenging topic that still is not completely understood. Several studies and theories, focused on kinematic and grasping tasks have been developed. In the next section, I will give an introduction on the most recent studies which focus on important aspects of manipulation: (i) hand control in pre-grasp phase, (ii) grasp force distributions, (iii) muscle activations, and (iv) impedance control.

2.1 Hand Control in Pre-grasp Phase

In manipulation tasks, reaching an object with the hand is not an obvious action; multiple degrees of freedom must be controlled to arrange hand shape. However, recent studies show a reduction in the number of DoFs independently controlled by the nervous system [1]. In [2], authors defined a map of postural synergies for

A. Altobelli, *Haptic Devices for Studies on Human Grasp and Rehabilitation*,
Springer Series on Touch and Haptic Systems,
DOI 10.1007/978-3-319-47087-0_2

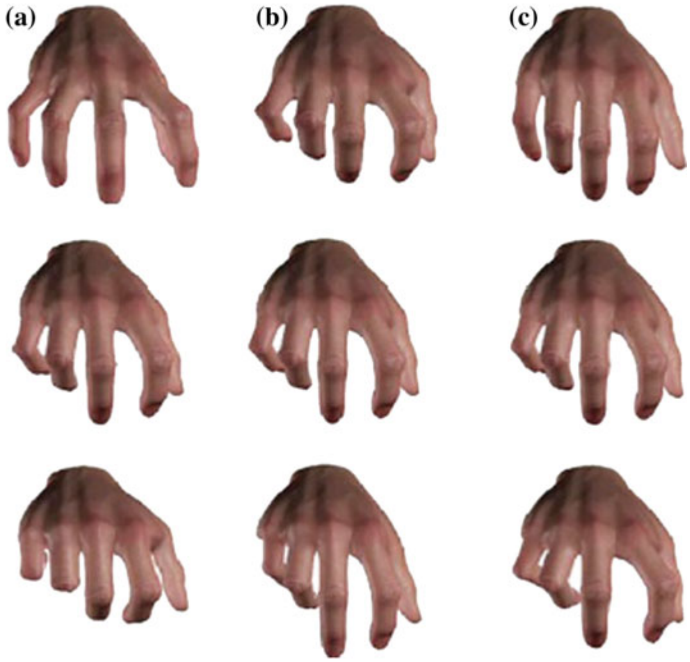

Fig. 2.1 The first three postural synergies in human hand: **a** first, **b** second, and **c** third

grasping movements. In their experiments, subjects grasp a large set of imagined objects, and then, PCA is performed with hand posture measures (Fig. 2.1 shows the synergies corresponding to the first three principal components). In this setup, without contact between object and hand, it is possible to examine how the central nervous system plans hand posture as a function of object shape.

To grasp a real object, more synergies are required to explain the hand configurations as shown in [3].

This study showed how the first three principal components described more "basic" patterns of finger motion such as hand opening/closing caused by motion at all metacarpal–phalangeal or proximal–inter phalangeal joints. Information provided by remaining synergies could be ignored in the reconstruction of postures. The findings suggest that few synergies could be involved to control the pre-grasp phase. This assumption could be supported by the work in [4], where synergistic finger movements are observed with transcranial magnetic stimulation (TMS) of the primary motor cortex; this behavior suggests that a modular hand muscle representation exists in human motor cortex. The CNS may be able to select the pattern of muscle activation from the identified synergies and partially involve anatomical constrains.

2.2 Grasp Force Distribution

To grasp and hold an object, the resultant of all forces exerted on the object has to be equal to zero. It is easy to see that an infinite number of contact force combinations could satisfy the last assertion; this topic is known in robotics as the force close and form closure problem [5]. While this problem is partially solved in robotics, in humans it is still not clear how the CNS distribute the forces at each contact point in grasping tasks. Strategies and constraints arise in several studies that aim to understand contact force distribution in humans. For example, exerting forces only with one finger when multiple fingers are in contact is impossible for humans as shown in [6–8]. The constraints appear also in kinematic as the phenomenon called “enslaving” [9]. In [10], the authors investigated the possible relation between normal forces in multifinger grasp, and in [11], they showed some coordination patterns which could be task dependent. A large intertrial variability in the normal forces exerted by each finger arise in [12]; these results, along with a coordinated action of each finger, lead authors to propose the existence of hierarchical control in manipulation action. The force modes are proposed to explain how the CNS controls the force distribution at each finger; in this theory, at each finger is linked a force pattern called force modes. Force distribution in grasping tasks could be a result of a coordinated action of force modes; however, it is not clear how many degrees of freedom are exploited by the CNS because it is evident that force modes depend on the task [13] and subjects [14].

A different strategy, called the uncontrolled manifold hypothesis, arises from analysis of contact force component variability and is used to explain and quantify synergies [15]. In this theory, two classes of variables are defined: (i) elemental variables related to parts of systems and (ii) performance variables related to the task. This classification is used to define bad-variance (VB), variability of elements that could affect the precision of task, and good-variance (VG), variability of elements that do not affect the performance. The ratio VG/VB could identify strong synergies or weak synergies if it is large or small.

Virtual finger hypothesis is also used to explain force distribution in multifinger grasp. It asserts that one or more virtual fingers are controlled by the CNS at a high level [16]. At a lower level for each contact point, forces exerted by each finger are modulated to hold constrains of VF. In the virtual finger hypothesis, contact forces at each finger continue to be redundant and not constrained as in forces modes.

In all these theories where hierarchical control plays an important role, some variables remain unassigned. To solve the remaining redundancy, optimal control theory could be used minimizing a suitable cost function which takes into account appropriate constraints; this approach allows to find solutions that could be not compatible with humans strategies. Recent theories propose that the CNS could exploit some biological proprieties of the system to adapt itself to the task. In a grasping task, the hand could adapt itself to the grasped object exploiting finger stiffness [17, 18]. To explain synergies showed by humans in holding tasks, recent works

[19, 20] introduce equilibrium point and reference configuration hypothesis that assume the existence of hand configurations at which all the involved muscles would achieve zero activation levels.

2.3 Muscle Activity

To study human motor control, muscle activity is another factor to take into account. Each hand articulation is moved by one or more muscles with a contraction or co-contraction activity. To monitor muscle and motor unit activation, electromyographic (EMG) signals could be exploited. Focusing on the hand, which includes a large number of muscles (Fig. 2.2), EMG signal is used to investigate spatial and temporal coordination of multiple muscles in disparate tasks. The correlation analysis of EMG signals resulted in coordination patterns in muscle activation; these pattern could induce muscle synergies. This hypothesis is supported by observation of two-digit force production [21, 22], three-digit object hold [23, 24], and whole-hand grasping [25]. In [26], focused on index finger, authors studied EMG signals of seven muscles throughout force production in several directions; finally, they show high muscle correlation in the task-relevant subspace instead of task-irrelevant subspace. This assertion suggests that only a reduced number of muscle activation patterns are employed by the CNS. In static grasp, it is also observed that a common neural input

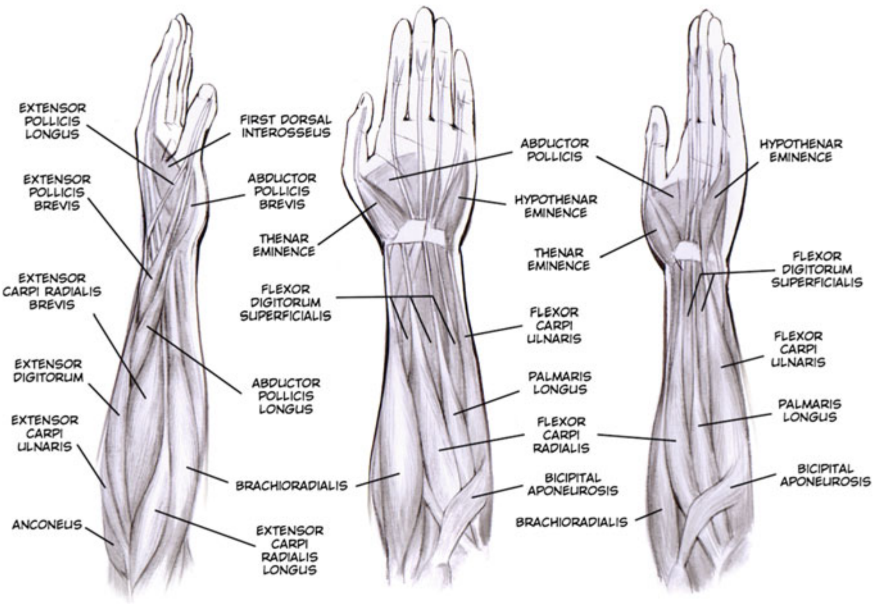

Fig. 2.2 An overview of the muscles that cooperate to move human hand

signal at hand muscles is heterogeneously distributed across the fingers, exiting in particular extrinsic muscles instead of intrinsic muscles [23, 24, 27]. This finding suggests that a strong correlation lies in hand muscle activation in grasping and non-grasping tasks.

2.4 Impedance Control

Stability and manipulability in grasping tasks can be affected by an other import factor: the impedance at the contact point. This property relates contact forces and contact point motion. To define impedance for each contact point, two main factors must be considered: static components (stiffness) and dynamic components (damping and inertia). Although both impedance components are studied in robotics and biomechanics for the upper limb [28–31]; only a few aspects of finger impedance have been investigated. In [32], the authors evidence the ability of hand motor control to modulate the antagonist co-contraction activity for different tasks: monitoring limb position, decelerating the limb in ballistic movements, and increasing stiffness [32]. Stiffening behavior can be realized to stabilize movement or to fix posture in isometric tasks [33]. Previous work examining finger and hand stiffness has explored various topics including the mechanical impedance of the fingers [34] or at the fingertip [35], pinch grasp stiffness during an isometric grasp task [36], or variance of stiffness depending on finger force or posture [37]. The estimation of the impedance parameters in these studies is mainly achieved by an off-line postprocessing phase, imposing severe limitations in real-time applications such as teleimpedance control of the prosthetic or robotic hands which require that the motion and the stiffness profiles of the fingers are appropriately commanded. At first, this might imply that an individual modeling and control of the finer motion and stiffness trajectories are required to perform a target manipulation task. However, observations in human motor control suggest that central nervous system solves for this complexity in an elegant and coordinated manner which has been well-recognized with the concept of hand synergies [38, 39]. While the exploitation of this concept in kinematic coordinates has lead to the development of several simple, effective and adaptive robotic designs and control strategies (e.g., see [39, 40]), its extension to dynamic coordinates, such as coordinated stiffening of the hand fingers, remain to be investigated. In [35], the authors found a linear relationship between fingertip stiffness and muscle activation for the metacarpal (MCP) joint of index finger. However, when multiple joints are activated in the same finger, the previous relationship collapses and finger postures along with voluntary forces contribute to changes in the stiffness ellipsoid at fingertip [37].

Several additional properties on human stiffness control arise from multifinger grasp studies.

In [40], authors show a relationship between grasp stability and symmetric components of stiffness matrix in thumb–index grasp. Focusing on three-digit grasp, the

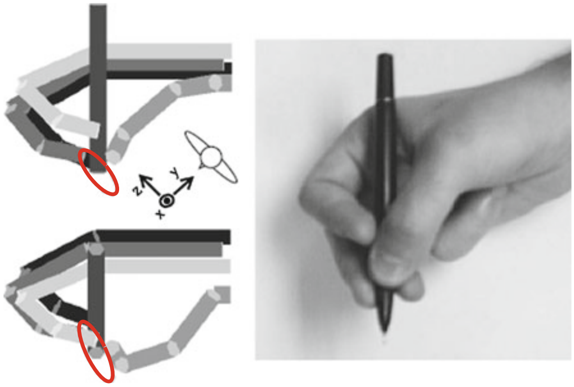

Fig. 2.3 An example of grasp stiffness adopted by human during the grasp of a pen

grasp stiffness was analyzed at changing of: (i) finger position and orientation [41], as shown in Fig. 2.3, and (ii) span and grasp force [42].

A possible relationship between the orientation of ellipsoids and salient task requirements results also in [43] where the authors investigate more in depth finger stiffness in grasping task of several rigid objects without restriction on contact point positions.

These results suggest that impedance control can improve performance of manipulation tasks in humans as in robot [44].

2.5 Outstanding Aspects in Grasping Task

Thus far, studies on multidigit grasp have focused on impedance and control of finger forces during manipulation of rigid objects. There are only a few studies that have investigated how humans grasp deformable or soft objects, despite the fact that hardness/softness is an important characteristic of objects [45] and one of the first haptic cues which infants can use to discriminate objects and squeeze them in their hands [46]. Furthermore, the constraints and control strategies involved in manipulating fragile or deformable objects might differ from those involved in the manipulation of rigid objects. For example, avoiding large contact forces might be crucial to avoid deforming or breaking them. The grasp might also be more or less stable depending on the properties of the object. The effect of compliance when holding an object with the tripod grasp was investigated in [47] with a device where a spring was placed below each contact. The control of the contact force when holding a fragile objects with a prismatic grasp was investigated in [48] with a device that collapsed when the contact force exceeded some threshold. The role of cutaneous information (related to direct deformation of the skin) vs. kinesthetic information (related to force indentation sensing) is an unknown aspect in grasping task; the brain uses this information to estimate stiffness at contact points, but how cutaneous information influences force distribution in a grasping task remains unknown. Finally, the stiffness influences the force distribution when humans grasp an object, but we do not know how the motor control is affected by stiffness.

The aim of this chapter is to introduce briefly some of most important factors that influence human motor control in grasping tasks. At the same time, this description should underline the complexity that characterizes factor manifold typically involved throughout the interaction between hand and grasped object. What is noticeable from this brief description is that a better understanding of human grasp is possible only by exploiting devices able to produce a complete set of measurements; in effect, contact points, forces and torques exerted by the hand, object stiffness, and muscle activation are necessary measures to study hand–object interaction.

From an engineering point of view, two approaches are used to develop devices to study human grasp: (i) sensorized objects (Figs. 2.4 and 2.5) and (ii) wearable devices (Figs. 2.6 and 2.7). The first solution requires the assembly of one or more sensors around a rigid frame; these devices allow the complete measurements of force and torque at the contact point, but usually they constrain hand posture. Wearable systems aim to guarantee unrestrained interaction of hand in grasping task; pressure sensor

Fig. 2.4 The grasp perturbator [49]

Fig. 2.5 The patched intrinsic tactile object [50]

Fig. 2.6 The stretchable fingernail sensors [51]

Fig. 2.7 The Tekscan pressure sensors [52]

on gloves and nail color analysis are two solutions presented in the literature. The limits of this approach usually are lack of contact point position and lack of complete force/torque measurements. The two approaches presented above (also referred to as “human-side” and “object-side,” respectively) exhibit pros and cons, and it is difficult (if not impossible) to design a system that can fully measure the physical interaction that occurs between hand and object throughout arbitrary manipulation tasks. It is more profitable to consider these two approaches complementary and necessary for a complete study of human grasp and rehabilitation systems.

In the first part of this book, I propose some devices to study grasp properties following two different approaches: (i) sensorized objects and (ii) wearable devices to measure force and torque. In the second part of this book, the sensorized objects are exploited in two different studies to investigate stiffness regulation principles in humans. The first study provides evidence of the existence of coordinated stiffening patterns in human digits and establishes initial steps toward a real-time and effective modeling of finger stiffness in tripod grasp. The second study presents experimental findings on how humans modulate their hand stiffness while grasping objects of varying levels of compliance.

References

1. J.F. Soechting and M. Flanders, "Flexibility and repeatability of finger movements during typing: Analysis of multiple degrees of freedom", Journal of computational neuroscience, vol. 4, no. 1, pp. 29-46, 1997
2. M. Santello, M. Flanders, and J.F. Soechting, "Postural hand synergies for tool use", The journal of neuroscience, vol. 18, no. 23, pp. 10 105-10 115, 1998
3. M. Santello, M. Flanders, and J.F. Soechting, "Patterns of hand motion during grasping and the influence of sensory guidance", The journal of neuroscience, vol. 22, no. 4, pp. 1426-1435, 2002
4. R. Gentner, J. Classen, Modular organization of finger movements by the human central nervous system. Neuron **52**(4), 731–742 (2006)
5. A. Bicchi, M. Gabiccini, M. Santello, Modelling natural and artificial hands with synergies. Philosophical transactions of the royal society b: Biological sciences **366**(1581), 3153–3161 (2011)
6. Z.-M. Li, M. Latash, V. Zatsiorsky, Force sharing among fingers as a model of the redundancy problem. Experimental brain research **119**(3), 276–286 (1998)
7. K.T. Reilly and G.R. Hammond, "Independence of force production by digits of the human hand", Neuroscience letters, vol. 290, no. 1, pp. 53-56, 2000. 21 Human Hand Motor Control Studies
8. V.M. Zatsiorsky, Z.-M. Li, M.L. Latash, Enslaving effects in multi-finger force production. Experimental brain research **131**(2), 187–195 (2000)
9. S.L. Kilbreath, S.C. Gandevia, Limited independent flexion of the thumb and fingers in human subjects. J physiol **543**, 289–296 (2002)
10. M. Santello, J.F. Soechting, Force synergies for multifingered grasping. Experimental brain research **133**(4), 457–467 (2000)
11. M.P. Rearick, A. Casares, M. Santello, Task-dependent modulation of multi-digit force coordination patterns. Journal of neurophysiology **89**(3), 1317–1326 (2003)
12. M.L. Latash, J.F. Scholz, F. Danion, and G. Schöner, "Structure of motor variability in marginally redundant multifinger force production tasks", Experimental brain research, vol. 141, no. 2, pp. 153-165, 2001
13. H.B. Olafsdottir, M.L. Latash, and V.M. Zatsisorsky, "Is the thumb a fifth finger?", Studies of digit interaction during force production tasks, 2005
14. F. Gao, S. Li, Z.-M. Li, M.L. Latash, V.M. Zatsiorsky, Matrix analyses of interaction among fingers in static force production tasks. Biological cybernetics **89**(6), 407–414 (2003)

15. J.P. Scholz and G. Schöner, “The uncontrolled manifold concept: Identifying control variables for a functional task”, Experimental brain research, vol. 126, no. 3, pp. 289-306, 1999
16. T. Iberall, G. Bingham, M. Arbib, Opposition space as a structuring concept for the analysis of skilled hand movements. Experimental brain research series **15**, 158–173 (1986)
17. D.J. Ostry, A.G. Feldman, A critical evaluation of the force control hypothesis in motor control. Experimental brain research **153**(3), 275–288 (2003)
18. M. Gabiccini and A. Bicchi, “On the role of hand synergies in the optimal choice of grasping forces”, in Robotics science and systems, 2010
19. J.-F. Pilon, S.J. De Serres, A.G. Feldman, Threshold position control of arm movement with anticipatory increase in grip force. Experimental brain research **181**(1), 49–67 (2007)
20. M.L. Latash, J. Friedman, S.W. Kim, A.G. Feldman, V.M. Zatsiorsky, Prehension synergies and control with referent hand configurations. Experimental brain research **202**(1), 213–229 (2010)
21. F.J. Valero-Cuevas, F.E. Zajac, C.G. Burgar, Large index-fingertip forces are produced by subject-independent patterns of muscle excitation. Journal of biomechanics **31**(8), 693–703 (1998)
22. F.J. Valero-Cuevas, Predictive modulation of muscle coordination pattern magnitude scales fingertip force magnitude over the voluntary range. Journal of neurophysiology **83**(3), 1469–1479 (2000)
23. A. Danna-Dos Santos, B. Poston, M. Jesunathadas, L. R. Bobich, T. M. Hamm, and M. Santello, “Influence of fatigue on hand muscle coordination and emg-emg coherence during threedigit grasping”, Journal of neurophysiology, vol. 104, no. 6, pp. 3576- 3587, 2010
24. B. Poston, A. Danna-Dos Santos, M. Jesunathadas, T. M. Hamm, and M. Santello, “Force-independent distribution of correlated neural inputs to hand muscles during three-digit grasping”, Journal of neurophysiology, vol. 104, no. 2, pp. 1141-1154, 2010. 23 Human Hand Motor Control Studies
25. E.J. Weiss, M. Flanders, Muscular and postural synergies of the human hand. Journal of neurophysiology **92**(1), 523–535 (2004)
26. F.J. Valero-Cuevas, M. Venkadesan, E. Todorov, Structured variability of muscle activations supports the minimal intervention principle of motor control. Journal of neurophysiology **102**(1), 59–68 (2009)
27. S.A. Winges, M. Santello, Common input to motor units of digit flexors during multi-digit grasping. Journal of neurophysiology **92**(6), 3210–3220 (2004)
28. F.A. Mussa-Ivaldi, N. Hogan, E. Bizzi, Neural, mechanical, and geometric factors subserving arm posture in humans. The journal of neuroscience **5**(10), 2732–2743 (1985)
29. T. Flash, F. Mussa-Ivaldi, Human arm stiffness characteristics during the maintenance of posture. Experimental brain research **82**(2), 315–326 (1990)
30. T. Tsuji, P.G. Morasso, K. Goto, K. Ito, Human hand impedance characteristics during maintained posture. Biological cybernetics **72**(6), 475–485 (1995)
31. A. Ajoudani, N.G. Tsagarakis, A. Bicchi, Tele-Impedance: Teleoperation with impedance regulation using a body-machine interface. International journal of robotics research **31**(13), 1642–1655 (2012)
32. A.M. Smith, The coactivation of antagonist muscles. Canadian journal of physiology and pharmacology **59**(7), 733–747 (1981)
33. D.R. Humphrey, D.J. Reed, Separate cortical systems for control of joint movement and joint stiffness: Reciprocal activation and coactivation of antagonist muscles. Adv neurol **39**, 347–372 (1983)
34. A.E. Fiorilla, F. Nori, L. Masia, G. Sandini, Finger impedance evaluation by means of hand exoskeleton. Annals of biomedical engineering **39**(12), 2945–2954 (2011)
35. A.Z. Hajian, R.D. Howe, Identification of the mechanical impedance at the human finger tip. Journal of biomechanical engineering **119**(1), 109–114 (1997)
36. H. Hoppner, D. Lakatos, H. Urbanek, C. Castellini, P. van der Smagt, “The grasp perturbator: Calibrating human grasp stiffness during a graded force task”, in Robotics and automation (icra), ieee international conference on. IEEE **2011**, 3312–3316 (2011)

37. T.E. Milner, D.W. Franklin, Characterization of multijoint finger stiffness: Dependence on finger posture and force direction. Biomedical engineering, ieee transactions on **45**(11), 1363–1375 (1998)
38. M. Turvey, Action and perception at the level of synergies. Human movement science **26**(4), 657–697 (2007)
39. M. G. Catalano, G. Grioli, A. Serio, E. Farnioli, C. Piazza, and A. Bicchi, "Adaptive synergies for a humanoid robot hand", in Ieee-ras international conference on humanoid robots, Osaka, Japan, In Press
40. I. Kao, M. R. Cutkosky, and R. S. Johansson, "Robotic stiffness control and calibration as applied to human grasping tasks", Robotics and automation, ieee transactions on, vol. 13, no. 4, pp. 557-566, 1997. 25 Human Hand Motor Control Studies
41. P. Buttolo, "Characterization of human pen grasp with haptic displays", PhD thesis, Citeseer, 1996
42. C.L. Van Doren, Grasp stiffness as a function of grasp force and finger span. Motor control **2**(4), 352–378 (1998)
43. J. Friedman, T. Flash, Task-dependent selection of grasp kinematics and stiffness in human object manipulation. Cortex **43**(3), 444–460 (2007)
44. N. Hogan, Impedance control: An approach to manipulation: Part ii?implementation. Journal of dynamic systems, measurement, and control **107**(1), 8–16 (1985)
45. S.J. Lederman, R.L. Klatzky, Relative availability of surface and object properties during early haptic processing. Journal of experimental psychology: Human perception and performance **23**(6), 1680 (1997)
46. P. Rochat, Mouthing and grasping in neonates: Evidence for the early detection of what hard or soft substances afford for action. Infant behavior and development **10**(4), 435–449 (1987)
47. S.A. Winges, S.E. Eonta, J.F. Soechting, M. Flanders, Effects of object compliance on three-digit grasping. Journal of neurophysiology **101**(5), 2447–2458 (2009)
48. S.L. Gorniak, V.M. Zatsiorsky, M.L. Latash, Manipulation of a fragile object. Experimental brain research **202**(2), 413–430 (2010)
49. H. Hoppner, J. McIntyre, P. van der Smagt, Task dependency of grip stiffness. a study of human grip force and grip stiffness dependency during two different tasks with same grip forces. Plos one **8**(12), e80889 (2013)
50. A. Serio, E. Riccomini, V. Tartaglia, I. Sarakoglou, M. Gabiccini, N. Tsagarakis, and A. Bicchi, "The patched intrinsic tactile object: A tool to investigate human grasps", 2014
51. J.M. Abu-Khalaf, J.W. Park, D.J. Mascaro, S. Mascaro, "Stretchable fingernail sensors for measurement of fingertip force", in Eurohaptics conference, et al., and symposium on haptic interfaces for virtual environment and teleoperator systems. world haptics 2009. third joint. IEEE **2009**, 625–626 (2009)
52. Tekscan, https://www.tekscan.com

http://www.springer.com/978-3-319-47086-3

Haptic Devices for Studies on Human Grasp and
Rehabilitation
Altobelli, A.
2016, XVI, 82 p. 64 illus., 60 illus. in color., Hardcover
ISBN: 978-3-319-47086-3